Lake Fertilization: State of the Art after 7 Years of Application

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October 1984

Canadian Technical Report of Fisheries and Aquatic Sciences No. 1324

85-3931/

Canadian Technical Report of Fisheries and Aquatic Sciences

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LAKE FERTILIZATION: STATE OF THE ART AFTER 7 YEARS OF APPLICATION

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Cat. No. Fs 97-6/1324E ISSN 0706-6457

Correct citation for this publication:

Stockner, J. G. and K. D. Hyatt. 1984. Lake fertilization: state of the art after 7 years of application. Can. Tech. Rep. Fish. Aquat. Sci. 1324: 33 p.

ABSTRACT

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A review of what has been learned after seven years of fertilizing coastal lakes in British Columbia to increase sockeye salmon production is presented. Though all the evidence is not yet in and some assumptions need validation, information gathered over the past seven years strongly supports the view that lake fertilization is working and is clearly one of the most cost-effective techniques for sockeye enhancement. Increased production at primary and secondary trophic (food) levels has been seen in all fertilized lakes. Smolts leaving most fertilized lakes are larger than in the pretreatment condition, and observed marine survival of returning adults surpasses anticipated levels. Provision of new "optimal" escapement targets provided to regional managers by scientific staff working on some sockeye stocks in fertilized lakes has led and will lead in future to much greater adult production.

Before the technology can confidently be transferred to management, information is required in three basic areas: (1) the fertilizer application strategy for a variety of nursery lakes must be "fine tuned" to assure optimal trophic efficiency without creating wasteful energy "sinks", (2) we must validate in-lake survival estimates of juvenile sockeye in "untreated" lakes or in "treated" lakes where background data are available and, (3) we must determine whether empirical models relating fertilizer loads to trophic response developed for British Columbia coastal, fast-flushing lakes can be validly extrapolated to large, slow-flushing, dimictic interior lake systems.

A bibliography of program publications from 1977-1984 is provided as an Appendix.

Key words: lake fertilization, limnology, sockeye salmon, fish ecology

RÉSUMÉ

Stockner, J. G. and K. D. Hyatt. 1984. Lake fertilization: state of the art after 7 years of application. Can. Tech. Rep. Fish. Aquat. Sci. 1324: 33 p.

Le présent rapport est un sommaire de l'information recueillie après sept années de fertilisation des lacs côtiers de la Colombie-Britannique dans le but d'accroître la production de saumon rouge. Quoique toutes les données ne soient pas encore disponibles et que certaines hypothèses restent à prouver, l'information obtenue donne du poids à l'opinion selon laquelle la fertilisation lacustre est efficace et qu'elle est sans contredit une des techniques les plus rentables pour ce qui est de la mise en valeur du saumon rouge. Une production accrue aux niveaux trophiques primaire et secondaire a été décelée dans tous les lacs fertilisés. Les saumoneaux qui sortent de la plupart de ceux-ci sont plus gros qu'avant le traitement et la survie observée chez les adultes revenant du milieu marin dépasse les niveaux anticipés. Les nouveaux taux d'échappée optimale fournis aux gestionnaires régionaux par des scientifiques étudiant certains stocks de saumon rouge des lacs fertilisés ont mené et mèneront à une production d'adultes beaucoup plus élevée.

Avant de pouvoir en toute confiance transférer la technologie aux gestionnaires, on doit (1) perfectionner la stratégie d'application du fertilisant dans une variété de lacs d'alevinage afin d'assurer une efficacité optimale au niveau trophique sans créer un engloutissement dissipateur de l'énergie; (2) valider les estimations concernant la survie des saumons rouges juvéniles dans les lacs traités et non traités, dans les cas où des données historiques sont disponibles et (3) déterminer si les modèles empiriques, élaborés pour des lacs côtiers à renouvellement rapide de la C.-B. et mettant en rapport les charges de fertilisant et la réaction trophique, peuvent être appliqués à de grands systèmes de lacs dimictiques intérieurs à renouvellement lent.

En appendice, on retrouvera une bibliographie des publications relatives au programme pour la période 1977-1984.

Mots-clés: fertilisation lacustre, limnologie, saumon rouge, écologie du poisson

INTRODUCTION

In 1977, under the auspicies of the Salmonid Enhancement Program (SEP), an expanded Lake Enrichment Program (LEP) was developed within the Fisheries Research Branch (FRB) to study and evaluate the efficacy of whole-lake fertilization of up to 15 sockeye salmon nursery lakes to enhance adult sockeye salmon production in the province (Fig. 1) (Stockner 1979). The program is functionally split into limnology and fish ecology components whose objectives are fertilization logistics and studies of lake response, and assessment of in-lake juvenile sockeye survival and growth and attendent adult production, respectively (Fig. 2). Based on program accomplishments and a positive adult production record, the LEP anticipates a greater involvement in meeting the Pacific region's sockeye production targets and hopes to expand to lakes of the Fraser River system and possibly transboundary lakes of the Stikine, Taku and Yukon river systems.

The objectives of this "state of the art" report are to highlight in very general terms the major accomplishments of the program over the past 7 years in research, production and assessment activities, and to identify future research and assessment requirements necessary to fill current gaps in knowledge pertaining to questions of "how" lake enrichment works.

WHAT WE HAVE LEARNED THUS FAR...

LAKE TREATMENT

Fertilizer. Lakes are treated with aqueous solutions of inorganic nitrogen (N) and phosphorus (P), prepared from dry agricultural fertilizer, the least expensive and most readily available source of N and P. Separate solutions of ammonium nitrate (NH_3NO_3) and ammonium phosphate ($(NH_3)_3PO_4$) are prepared and combined just prior to application to the lake in the desired N:P ratio, usually 15:1 on an atomic weight basis. We have examined the possibility of applying dry fertilizer directly to the lake and found the application costs to be similar to aqueous solutions, but the solubility within the lake's euphotic zone was the major difficulty, i.e. the material rapidly sinks out of the surface layer (K. Stephens, unpublished information). Other mixtures of fertilizers supplied by various manufacturers have been tested in a 6 m column of water located at the Pacific Biological Station (PBS), but none have proven to be as inexpensive nor produced the solubility and associated "available" nitrogen and phosphorus requirements of agricultural grade ammonium nitrate and phosphate. Tests of the efficacy of a single application of slow-release fertilizer pellets (Osmocote) for small lake fertilization began in May, 1984 in Muriel Lake.

Dosage Rates. Lakes are generally treated throughout the growing season (April to September) and fertilizer loads were calculated on a lake area (m^2) and growing season (20 to 26 weeks) basis e.g., mg·N and P·m^{-2}· growing season^{-1} or week^{-1}, using equations and computations discussed in detail by Stockner et al. (1980). Fertilizer loads vary from lake to lake depending on

physical, biological and hydrological considerations, and have ranged from lows of 2.5 to highs of 15.6 mg $P \cdot m^{-2} \cdot wk^{-1}$ which is usually about 60 percent of the natural load (Lp) (Costella et al. 1982, 1983). The best estimate of optimal load to achieve a favourable autotrophic response in most fast-flushing coastal lakes is about 4-6 mg $P \cdot m^{-2} \cdot wk^{-1}$ and 60-90 $mg \cdot N \cdot m^{-2} \cdot wk^{-1}$.

Application. The pros and cons and associated benefits and costs of aerial versus vessel applications of fertilizer to lakes has recently been dealt with in considerable detail by Stephens and Stockner (1983). In summary, their findings point to the superiority of the aerial method when dealing with more than a single lake treatment, i.e. it is far more economical to treat a suite of lakes by air than to establish mixing facilities and transport fertilizer, boats and ancillary equipment to each lake. A single lake of less than 1000 ha in size is more economically treated by vessel.

Application Frequency. Weekly additions covering a 20 to 26 week growing season commencing in April-May have thus far been most widely used; however, in 1983, 3 lakes received twice-weekly applications and preliminary results based on phytoplankton response look very encouraging. In 1978, Great Central Lake received weekly additions for only half of the growing season - May to August, with no apparent adverse effect on sockeye growth (T. Gjernes, unpublished data). An additional half growing season application experiment on Kennedy-Clayoquot is planned in 1985. Until results of the 1983 twice weekly application experiment have been fully analyzed and the second half-growing season experiment is assessed, weekly additions will continue as the most practical and cost-effective frequency of fertilizer application.

N:P Ratio. Initially a fertilizer nitrogen to phosphorus (N:P) ratio of 10:1 was used in all lake treatments (Stephens and Stockner 1983). Difficulties with nuisance blue-green algal blooms occurred in Kennedy-Clayoquot in 1980 and 1981, and commencing in 1982 an experiment was begun to attempt to control this undesirable condition by altering the fertilizer N:P ratio. The ratio was raised in successive years from the initial 10:1 (1978) to 15:1 (1979-81) to 26:1 (1982) to 35:1 (1983) while holding the phosphorus load constant, and the blue-green bloom was finally eliminated in 1983. The majority of lakes treated thus far have not developed blue-green blooms and have not required this N:P ratio adjustment; however, in those lakes where ambient concentrations of dissolved nitrogen are exceptionally low (spring overturn values of $<25\ \mu g \cdot L^{-1}$), this method of control can be used as an effective means of eliminating this type of undesirable nutrient "sink" and barrier to efficient energy flow to juvenile sockeye salmon.

In 1984, an experiment is planned to fertilize Nimpkish Lake with only ammonium phosphate at a very low loading rate (3.6 $mgP \cdot m^{-2} \cdot wk^{-1}$) and an N:P ratio of (3:1). This low N, low dosage treatment should reduce the abundance of the large, slow growing diatom Rhizosolenia that we believe is, like blue-greens in Kennedy-Clayoquot, an undesirable nutrient "sink" and another "bottleneck" to efficient energy flow in Nimpkish and other large coastal lakes e.g. Great Central, Henderson, and Sproat lakes.

LAKE RESPONSE

Bacteria. Numbers of free-living aquatic bacteria have increased in all treated lakes in response to the greater availability of organic substrates in the more productive and metabolically active surface waters of fertilized lakes (Fig. 3) (MacIsaac et al. 1981). Bacterial biomass estimates provide one of our most sensitive variables for predicting lake production (Fig. 4). Bacteria also serve as a valuable food source for herbivorous zooplankton, for some rotifers and for protozoa as well. In addition, their rapid turnover rates can increase the rate at which both nitrogen and phosphorus are recycled and made available to phytoplankton within the epilmnion of lakes.

Phytoplankton. There has been a marked increase in the standing stock (biomass) and growth (production) of phytoplankton in all fertilized lakes (Figs. 5,6). The strength of the phytoplankton response (see Stockner et al. 1980; Stockner and Shortreed 1984) varies as a function of the amount of phosphorus added to each lake (dosage rate) as is shown by the positive relation between weekly fertilizer load and average growing season phytoplankton biomass (chlorophyll) (Fig. 7). The size-frequency spectrum of the phytoplankton community is very important to the herbivorous zooplankton community, and accordingly research efforts have focussed over the past 7 years on measuring shifts in various size fractions in response to lake treatments.

Small picophytoplankton (<3 μm diam.) have been discovered to play a very important role in the carbon metabolism of coastal lakes and their rapid growth rates and generally great abundance in a grazeable size range underscores their potential importance as a food source for herbivorous zooplankton in treated coastal lakes. Larger net plankton (>50 μm diam.) are much less utilizeable as a food resource by zooplankton (Gliwicz 1975), and these forms have also increased in treated lakes, generally appearing as protracted spring diatom blooms or, in late-summer, either as surface blue-green blooms (Kennedy-Clayoquot) or as hypolimnetic plates (Great Central Lake). We believe the less desirable net plankton response to be closely related to fertilizer dosage rate, N:P ratios and application frequency, and experiments have been underway since 1982 to address the effects of each of these variables on the size spectrum shifts by the phytoplankton community so that in the future we may better "fine tune" our fertilizer additions to create the most desirable size and quality of phytoplankton for herbivorous zooplankton, thereby reducing or eliminating inefficient energy sinks.

Zooplankton. We have recorded an increase in zooplankton abundance in most treated lakes, and we attribute this increase to the greater abundance of their phytoplankton food resource (Fig. 8) (Rankin et al. 1979; Rankin and Ashton 1980). Effects of altered twice-weekly application frequency on zooplankton abundance and species composition have yet to be assessed, but based on the apparent strength of the autotrophic response to twice-weekly additions we believe that zooplankton have probably responded favourably as well. More rotifer species at elevated population densities appear in treated lakes, responding in all likelihood to the greater abundance of bacterial and picophytoplankton biomass in treated lakes. Experiments are planned for 1984 to examine the important phytoplankton-food-quality-size spectrum question as it relates to zooplankton grazing and subsequent population growth and fecundity.

Fish. Since the abundance of zooplankton has increased in fertilized lakes it is not unrealistic to expect sockeye to have benefited from this enhanced food resource. In the vast majority of treated lakes where pretreatment data are available for comparison, we have seen marked increases in October juvenile and spring smolt weights over the untreated condition (Hyatt and Stockner 1985). If one normalizes lake zooplankton abundance on a total planktivorous fish density basis (zool·fish^{-1}), then it appears that the best sockeye growth would be achieved in coastal lakes at food levels of 3-5 g zoopl·fish^{-1} over the growing season (Hyatt and Stockner 1985). Limnetic fish density also has an effect on sockeye in-lake growth and results to date suggest that at intermediate fish densities, lake fertilization has led to increases in smolt weights, ranging from 102% to 39% at densities of 500 to 3000 fish·ha^{-1}, respectively.

Limnetic sticklebacks can be an effective competitor of juvenile sockeye in some coastal lakes, and in Long Lake populations exhibited striking increases concomitant with the first year of fertilization in 1977. By autumn 1978, stickleback populations in the lake were estimated to be greater than 17 million and total limnetic fish densities exceeded 9000 fish·ha^{-1}. Sockeye smolts sampled in May, 1979 were of similar average size to those sampled before enrichment (2.3 g) and smolts from May, 1980 were only 1.2 g average weight. Following a two year hiatus in the fertilization of Long Lake, stickleback populations fell to 5 million by October, 1980 and to 4 million by October, 1981 (K. Hyatt, unpublished data). After seven years of treatment of up to 15 lakes, sticklebacks have not been a serious problem in the majority of lakes and research is underway to determine factors controlling stickleback numerical responses in the 3-5 lakes where they have been a problem.

Adult Production. With the exception of early returns from the initial experiment on Great Central Lake we have only returns from 1981, 1982 and 1983 with which to assess the adult salmon production potential of the expanded Lake Enrichment Program. Production performance is based on the comparisons of our predictions of adult returns expected under treated conditions against returns observed from 1981-83 (Table 1). Predicted returns from fertilized lakes are based on hydroacoustic juvenile population estimates and on an assumption that a given smolt year-class will exhibit an average 4.7% marine survival (SEP biostandard). It should be noted that this can only be done for 5 lakes where reliable catch and escapement information can be gathered. Observed returns are catch plus escapement for years 1981-83 (Table 1).

When predicted returns are compared with observed it is apparent that our predicted marine survival is about 60% too low because, on average, treated sockeye stocks to Great Central, Hobiton, Long and Henderson lakes are showing about a 7.3% marine survival. Thus, the biostandard for marine survival from fertilized lakes should probably be increased to reflect the currently observed trend.

Because we lack untreated data on within-lake and marine survival from Great Central, Hobiton, Henderson or Long lakes, we currently have no specific empirical basis for ascribing a set portion of adult production from treated lakes to effects of lake enrichment alone. However, based on observed smolt size increases (Hyatt and Stockner 1985), and assumed within-lake survival benefits we feel that at least 50% of current sockeye production from treated lakes is attributable to nutrient enrichment. Thus, of the 3,584,000 adult sockeye produced since 1981 from five treated systems (Table 1),

approximately 1,800,000 can be claimed with good justification to have been produced by the program. The real adult production since the expanded program began in 1977 is potentially much greater than this, but, at present we have no means of assessing with any confidence the necessary catch or escapement information for the remaining treated lakes due to their remote locations and sockeye interceptions in a variety of mixed stock fisheries.

An additional and as yet unrecognized benefit of the Lake Enrichment Program to sockeye production is advice to management regarding optimal escapements and in-lake limits on lake carrying-capacity for juvenile sockeye (Table 2). If our research and consultation with management had not taken place, escapement targets in all likelihood would have been left at historic levels and fish available for harvest from the four stocks listed in Table 2 would have ranged from 143,000 (untreated) to 400,000 (treated). However, by providing management with revised optimal escapement targets the theoretical harvest of fish available from these stocks is currently estimated to be about 1,200,000 fish (treated), and it is clear that the actual or realized catch in recent years has even surpassed this expectation (Table 2, row X). Thus, we feel that of the current average catch of 743,000 sockeye from the four stocks listed in Table 2, some 350,000 additional sockeye can be claimed to be a result of our program activities; namely, advice on optimal escapement targets and carrying-capacity for the treated systems. Another way of looking at this benefit is to say - 350,000 fish could potentially have been lost from the annual catch if management had adhered to historic escapement targets.

SUMMARY

After seven years of fertilizing 15 British Columbia lakes, we have learned much about the limnology and fish ecology of coastal lakes and have identified several key variables driving lake metabolism and determining levels of autotrophic and heterotrophic production. We have refined application frequencies, N:P ratios and dosage rates and created in some lakes an optimal phytoplankton food quality, and concomitantly the food resource (zooplankton) of rearing juvenile sockeye has been enhanced. The net result is the production of larger outmigrant smolts in the majority of treated lakes. Though the assessment of adult returns is possible only for 1980-83, results are very encouraging and indicate enhanced marine survivals, in excess of anticipated levels, with commensurate benefits both to the fishery and the escapement.

WHAT WE NEED TO KNOW...FURTHER RESEARCH

In a research and production program of this magnitude it is not surprising that many questions pertaining to how enrichment works and to how the technique can be made more efficient and cost effective remain unanswered. As the program moves to the large interior lakes of British Columbia further problems require answers and the validity of extrapolating

results from coastal lakes must be addressed, and further logistic problems 'of scale' face the program in the future.

We have attempted, therefore, to address some of the more pressing questions which require further research effort over the next few years. This list is divided into 3 components: (1) questions requiring immediate attention and directly applicable to the current coastal Lake Enrichment Program (designated A); (2) questions requiring immediate attention and related directly to the large interior B.C. dimictic lakes, (designated B) and (3) questions directly addressing "how" fertilization does or does not work and requiring further basic research before lake fertilization can evolve into a reliable and operational enhancement technique (designated C).

1. A — The major cost of treating lakes is that associated with aerial application. Therefore, we need to test the biological effectiveness and costs of alternative techniques for treating lakes (e.g. slow-release fertilizers, organic phosphorus, etc.).

2. C — Alternatives to chemical (N and P) fertilizer additions should be tested. This might include: induced upwelling, sediment manipulation (deoxygenation) to release absorbed nutrients, use of sewage or cannery wastes in small remote communities etc.

3. A — The program must continue to study the response of phyto and zooplankton communities to alternate fertilizer application strategies i.e., variable N:P ratios, coverage area, length of treatment, and application frequency. Such "fine tuning" to promote optimal trophic responses in nursery lakes could result in substantial savings and be very cost effective by increasing the efficiency of fertilization for enhancing the zooplankton food resource of juvenile sockeye.

4. A — Program personnel must continue to monitor selected lakes after fertilization is terminated to document the time required for a return to pretreatment steady-state conditions, and to obtain the necessary "control" data currently lacking for many systems.

5. B — Fertilizer loading criteria have been developed for fast-flushing, monomictic coastal lakes, but whether these same criteria can be applied to large dimictic, slow-flushing interior lakes is unknown. If fertilization of large interior British Columbia lakes is to be successful, further research may be required to modify our current techniques which were developed for coastal lakes.

6. B — Intensive prefertilization studies of interior British Columbia lakes are required to determine current baseline nutrient and productivity levels. This information is required for equations used to estimate fertilizer loads and to provide background data to assess the effectiveness of nutrient additions.

7. C — In a few of our coastal lakes (Great Central, Kennedy-Clayoquot, Nimpkish), fertilization has produced an increase in large net phytoplankton which likely do not enter the food-chain leading to sockeye salmon. Such "sinks" are undesirable as they impede energy transfer and reduce fertilization efficiency and further research is

needed to identify edible and inedible components of the phytoplankton and to determine fertilization strategies that discourage their growth while promoting the increase of edible pico- and nanophytoplankton.

8. The current program must complete the assessment of within-lake survival effects of fertilization on juvenile sockeye. To accomplish this will require 3-5 years of observations after
A termination of fertilization in 3-4 key study lakes (Great Central, Henderson, Hobiton) or alternately initiatives to experimentally manipulate small lakes specifically for the purpose of assessing effects of treatment on juvenile sockeye survival.

9. We need to further supplement our meager observations of effects of smolt size and time at release on marine survival by continuing to monitor total adult stocks for smolt year-class returns at selected
A key coastal lakes. In addition, coded-wire tag releases for time and size of release effects on marine survival of sockeye should begin using small, intensive study systems such as Hobiton and Muriel lakes to accelerate testing of critical assumptions about survival benefits of treatment.

10. The program should continue investigations of mechanisms of interactions among juvenile sockeye, their competitors and their zooplankton food resource. Research should be pursued to determine factors controlling stickleback numerical responses to fertilization
A
in the 3-5 lakes where they have unquestionably played a major role in reducing the flow of food-energy to juvenile sockeye. Further, it is uncertain whether the maintenance of large standing crops of unusually large zooplankton species (eg. Neomysis mercedis, Chaoborus spp.) in some coastal lakes represents, on balance, a sink or a source of energy for juvenile sockeye, thus futher study is required to define their importance in determining the success of lake treatments.

11. Because sockeye production in many systems is limited by suboptimal escapements and incubation-space limitations, studies should continue to observe relationships between optimal escapements,
C adequacy of incubation environment, and within-lake carrying capacity for selected stocks; and, as well, re-examine the feasibility of sockeye enhancement through development of small hatchery and transplant techniques.

12. The program should begin exploring the availability of and
C feasibility of utilizing barren lakes for rearing coho or chinook outplants from SEP hatcheries.

13. We should commence studies to determine the interactive effects of zooplankton species, size and behavior on their energetic value as prey items for juvenile sockeye. Between and within-lake variations in the size and species composition of zooplankton communities may significantly affect sockeye growth, but the importance of prey
C types has not been experimentally established nor have optim a prey

types been identified. Changes in the prey quality of the zooplankton induced by fertilizer applications may have enormous positive or negative effects on the growth of sockeye and will require intensive food-chain research in the future.

ACKNOWLEDGMENTS

Without the cooperation, commitment and dedicated research efforts over the past seven year of all Lake Enrichment Program staff, including contract employees, this review could not have been written. In addition, without the continued support of both SEP and FRB senior management the program could not have achieved its objectives.

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Table 1. Predicted and observed adult returns for years 1981-83 from 1978 and 1979 treated broods.

Lake	Smolts released X 10^6 1978	1979	Returns predicted*	Returns observed	O-P as % P
		Return year - 1981			
Great Central	8.67	14.69	589,642	848,000	+43.8
Henderson	1.40	1.11	56,331	47,000	-16.6
Hobiton	.36	.35	16,575	22,000	+32.9
Long	1.69	3.60	137,620	375,000	+192.5
Kennedy	2.34	1.80	92,768	N/A	
		Return Year - 1982			
	1979	1980			
Great Central	14.69	6.10	423,000	346,000	-18.2
Henderson	1.11	2.90	107,000	60,000	-43.9
Hobiton	0.35	0.34	12,000	75,000	+525.
Long	3.60	3.10	153,000	500,000**	+226.3
Kennedy	1.64	1.70	78,000	120,000**	+53.8
		Return Year - 1983			
	1980	1981			
Great Central	6.10	10.24	411,968	791,000	+92.0
Henderson	2.90	1.36	88,152	127,000	+44.06
Hobiton	.20	.52	19,164	28,000	+46.1
Long	3.10	1.84	106,088	220,000**	+109.4
Kennedy	.84	.79	37,456	25,000**	-33.3

*Predictions based on assumption of 1.6% smolt-adult survival for 1.3 and 2.2's and 3.0% survival on 1.2's.

**Estimates provided by Field Services Branch personnel.

Table 2. Increased adult sockeye production based on optimal instead of historical escapement targets and theoretical harvest strategies.

	Stock	Great Central	Sproat	Henderson	Hobiton
I.	Escapement Targets[1]	50,000	50,000	25,000	2,000-5,000
II.	Theoretical Harvest A[2] (Untreated)	55,000	55,000	27,500	2,200-5,500
III.	Theoretical Harvest B[3] (Treated)	160,000	160,000	80,000	6,400-1,600
IV.	Realized Escapement[4]	26,000	46,000	28,000	5,000
V.	Realized Catch[5]	←	60,756	→	1,900
	LAKE ENRICHMENT OPERATIONS AND RESEARCH				
VI.	Escapement Targets[6]	250,000	190,000	75,000	20,000
VII.	Theoretical Harvest B[3] (Treated)	800,000	608,000	240,000	64,000
VIII.	Realized Escapement[7]	219,249	136,086	27,709	15,042
XI.	Escapement[8]	236,038	189,469	40,541	23,566
X.	Realized Catch[9]	←	729,666	→	13,000

[1]Mean escapement target set by district manager.

[2]Assumes escapement target is met, Lake is not treated, sex ratio is 1/1, fecundity is 3,000 eggs.female^{-1}, egg-adult survival is .14%.

[3]As above except lake is treated and egg-to adult survival is .28%.

[4]Mean escapement achieved over 12 years preceeding LEP operations and research.

[5]Mean catch over 4 years preceeding LEP involvement.

[6]Escapement targets recommended by LEP sockeye ecology unit under assumption that spawning ground area is not limiting and treated lakes can produce 3,000 smolts per hectare.

[7]Mean escapement achieved during SEP Phase I (1977-1983).

[8]Mean escapements achieved since 1980 given continued consultation between FSB personnel and LEP personnel.

[9]Mean catch for 1981, 1982 and 1983 return years.

FIGURES

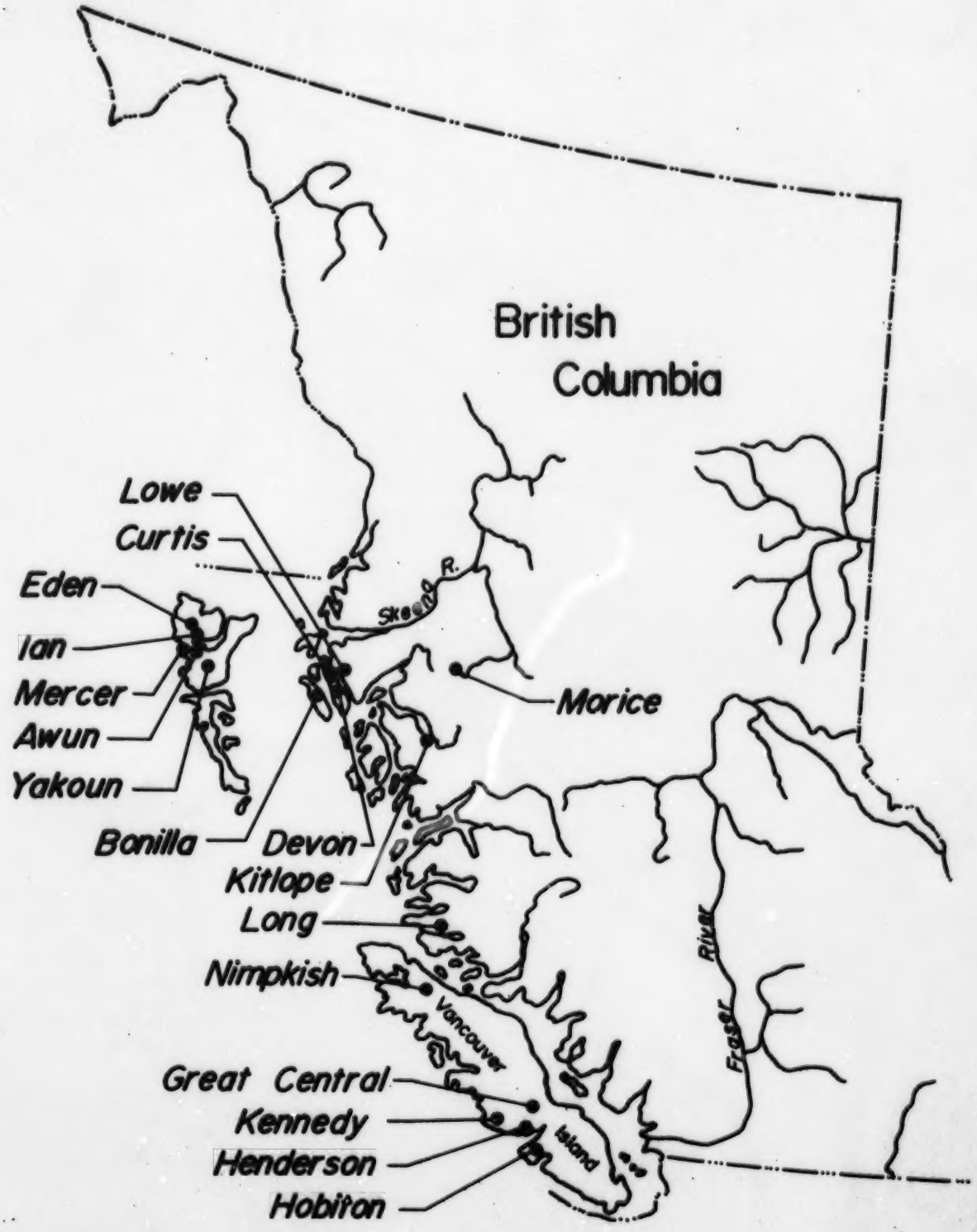


Figure 1. Map of British Columbia with location of fertilized lakes.

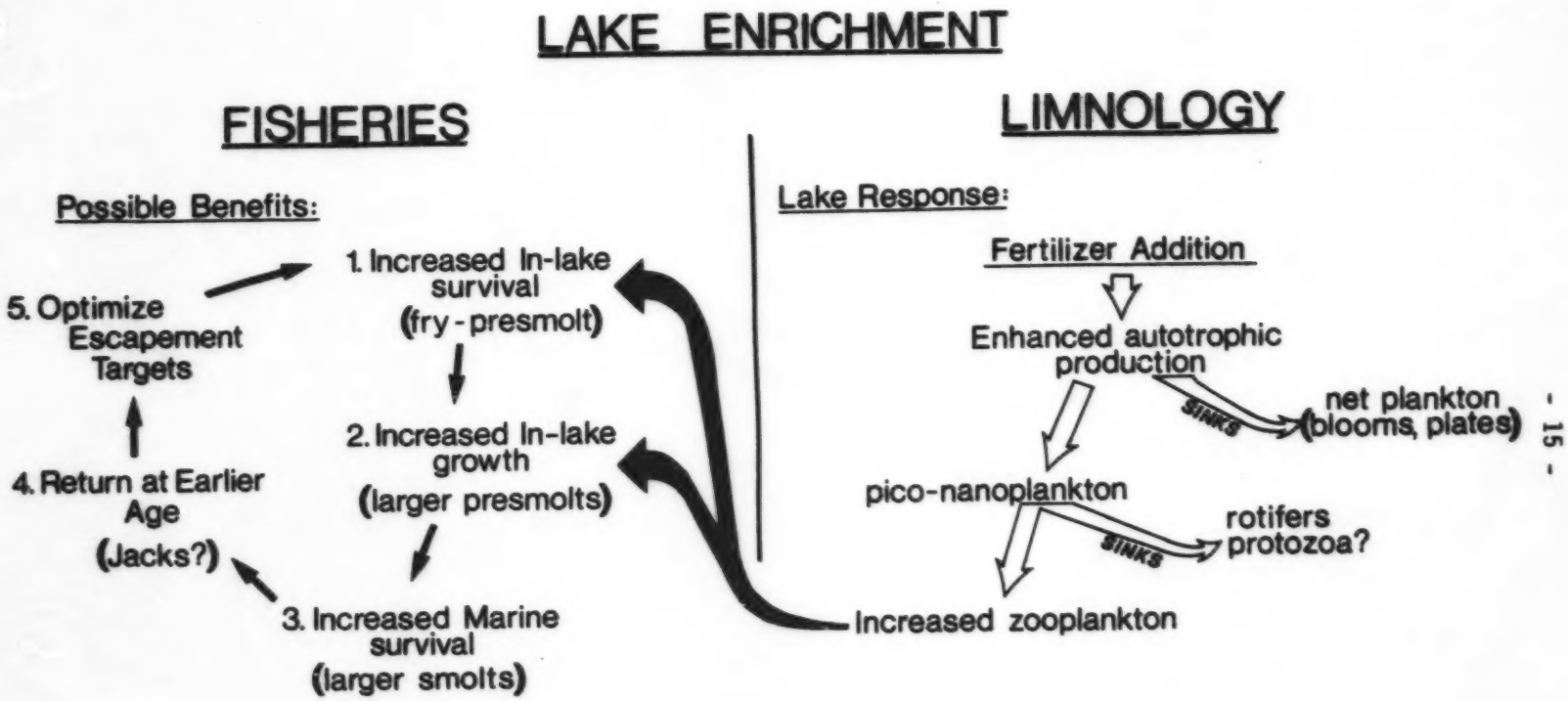


Figure 2. Components, objectives and expected benefits of British Columbia Lake Enrichment Program.

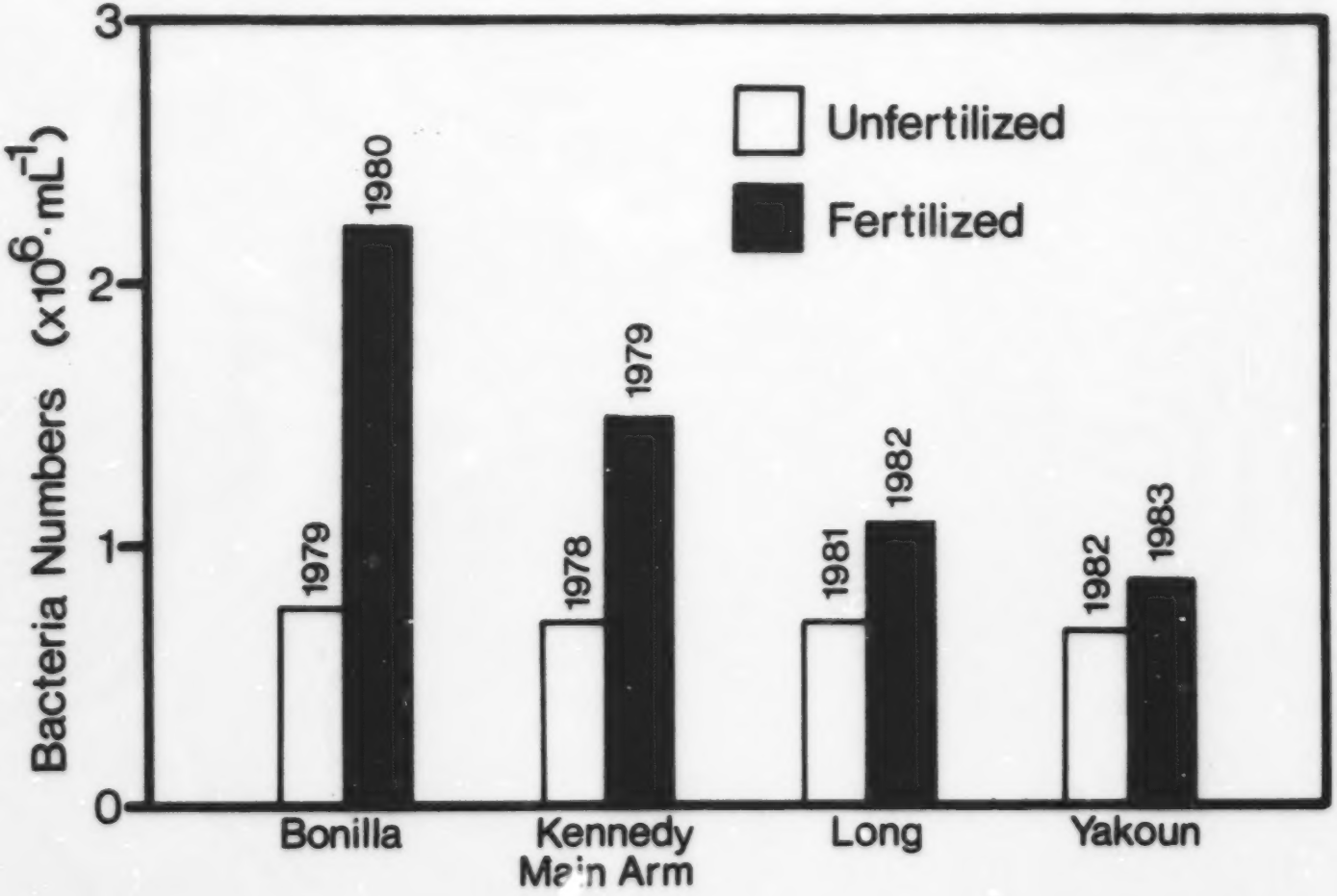


Figure 3. Seasonal average bacteria numbers ($x10^6 \cdot mL^{-1}$) in several coastal lakes in the year preceding and year of first fertilization.

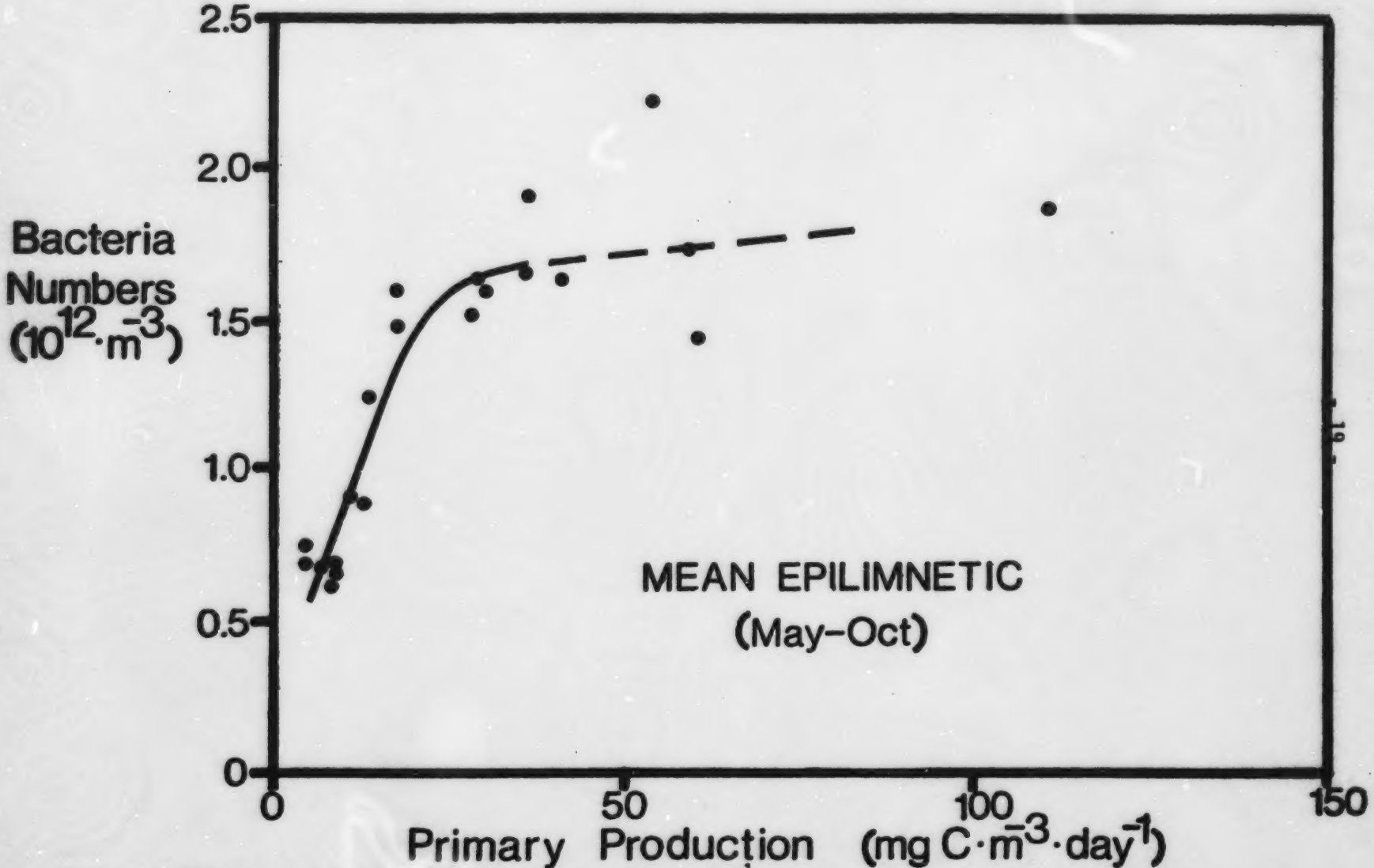
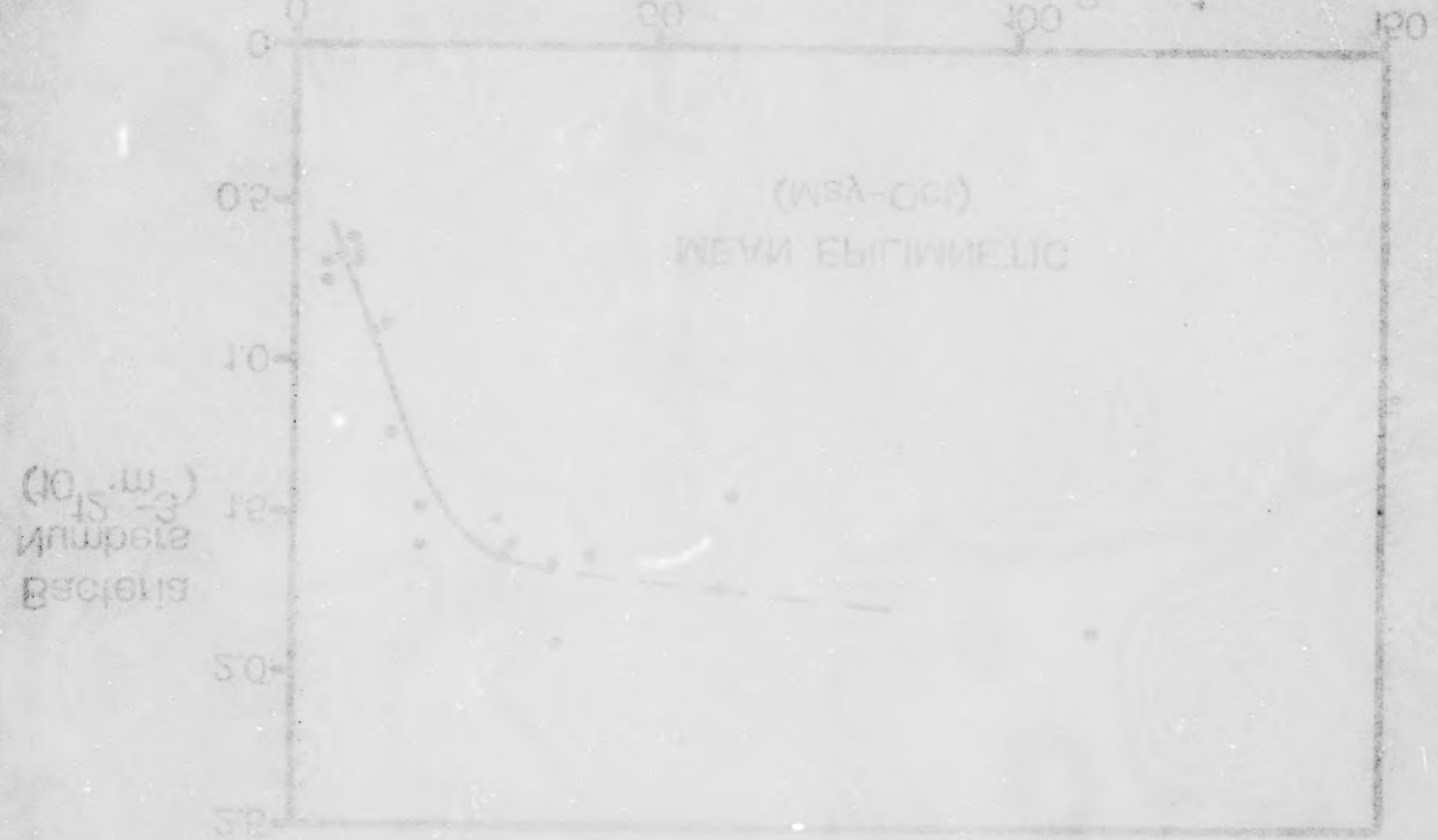


Figure 4. Relationship between average bacteria numbers $\cdot mL^{-1}$ and phytoplankton production in treated and untreated coastal lakes.



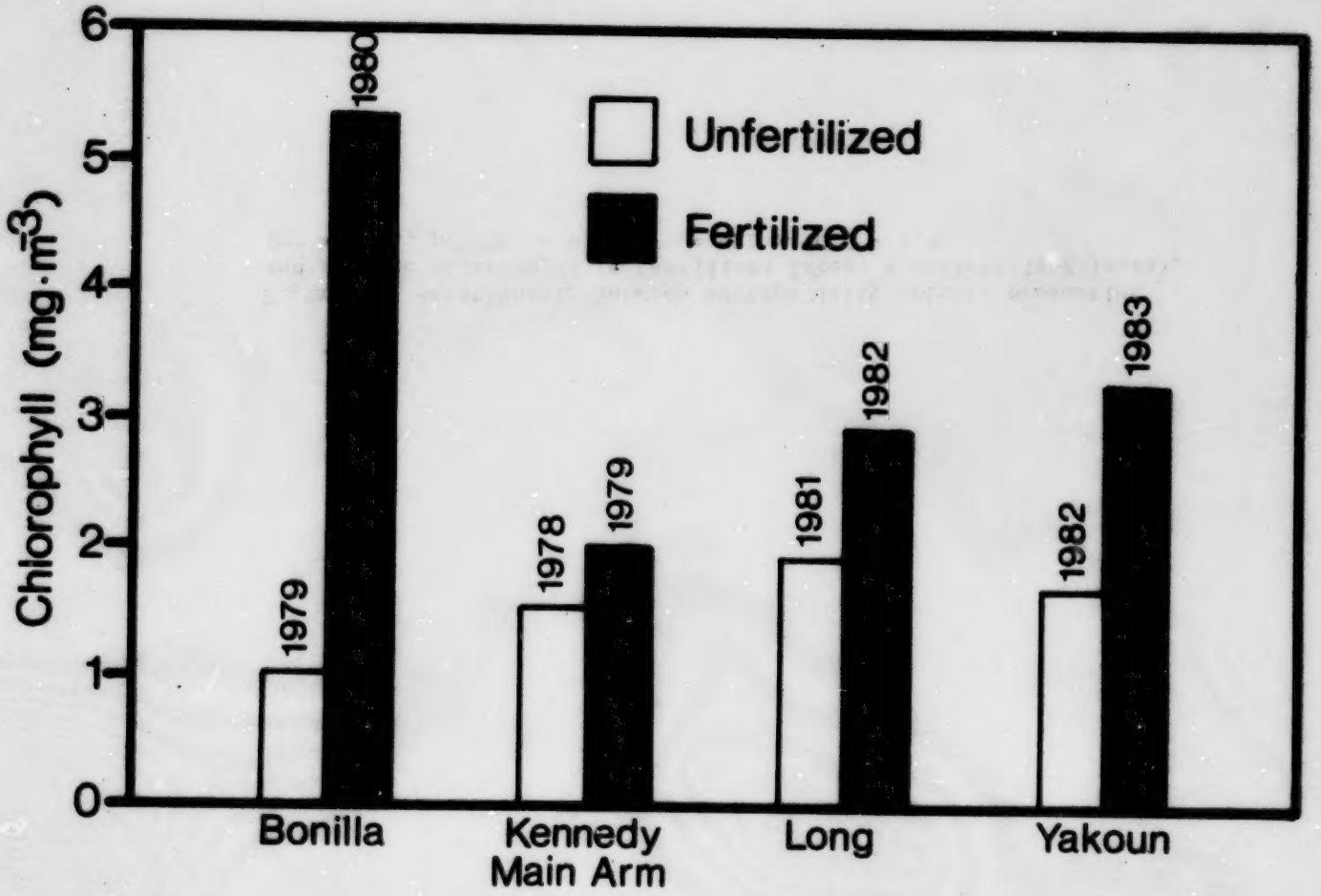


Figure 5. Seasonal average chlorophyll concentration ($mg \cdot m^{-3}$) in several coastal lakes in the year preceeding and year of first fertilization.

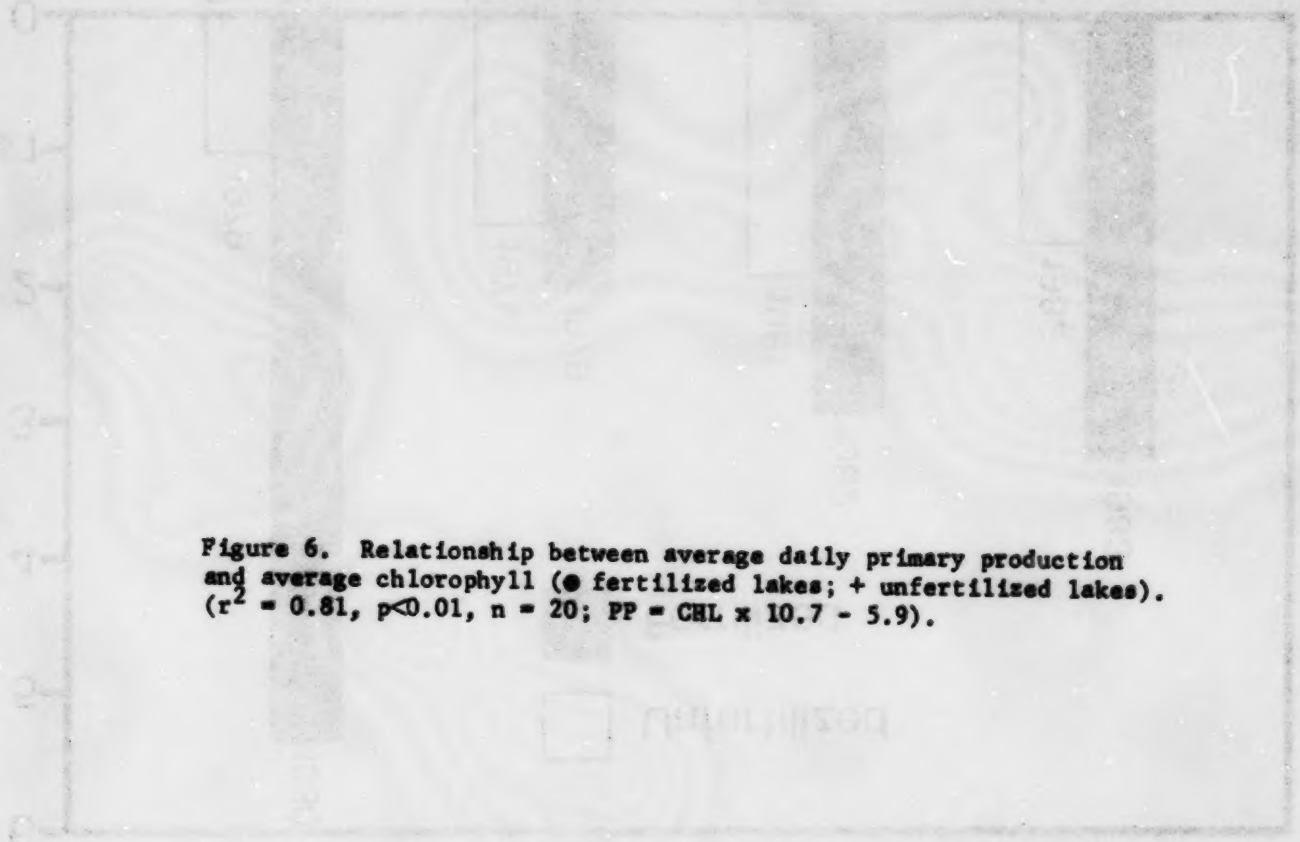
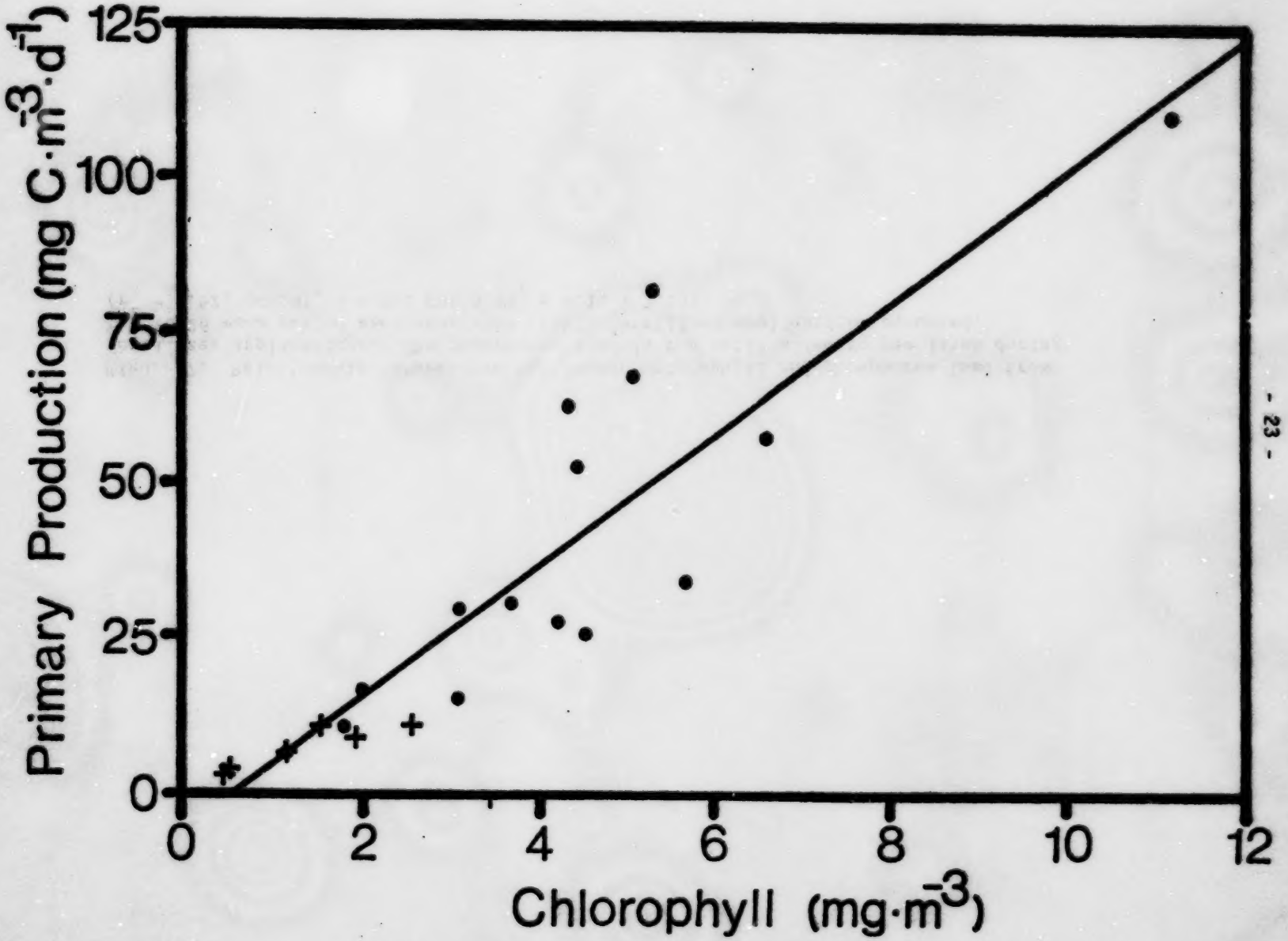


Figure 6. Relationship between average daily primary production and average chlorophyll (● fertilized lakes; + unfertilized lakes). (r^2 = 0.81, $p<0.01$, n = 20; PP = CHL x 10.7 - 5.9).


Primary Production (mg C·m⁻³·d⁻¹)
125
100
75
50
25
0
0
2
4
6
8
10
12
Chlorophyll (mg·m⁻³)

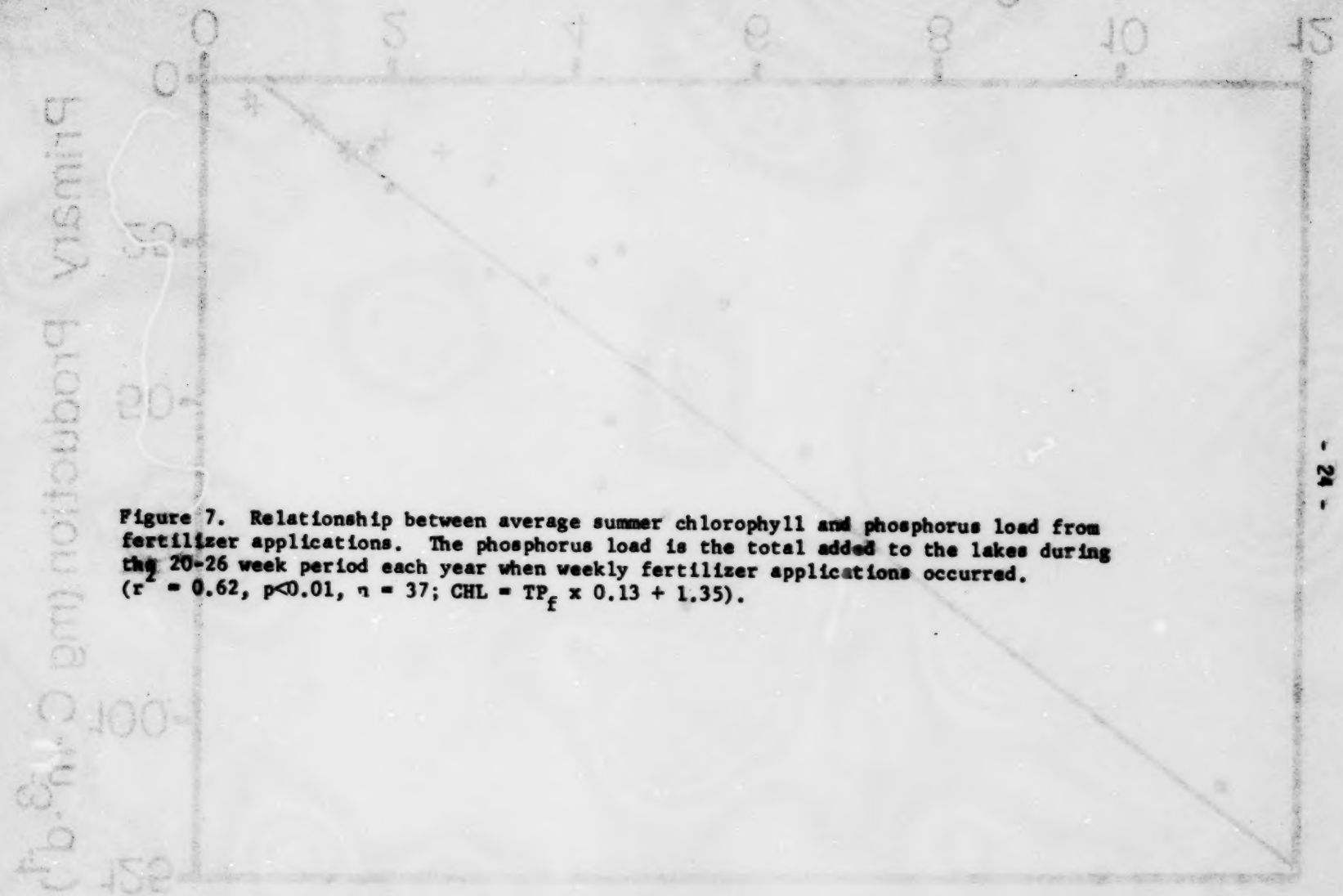
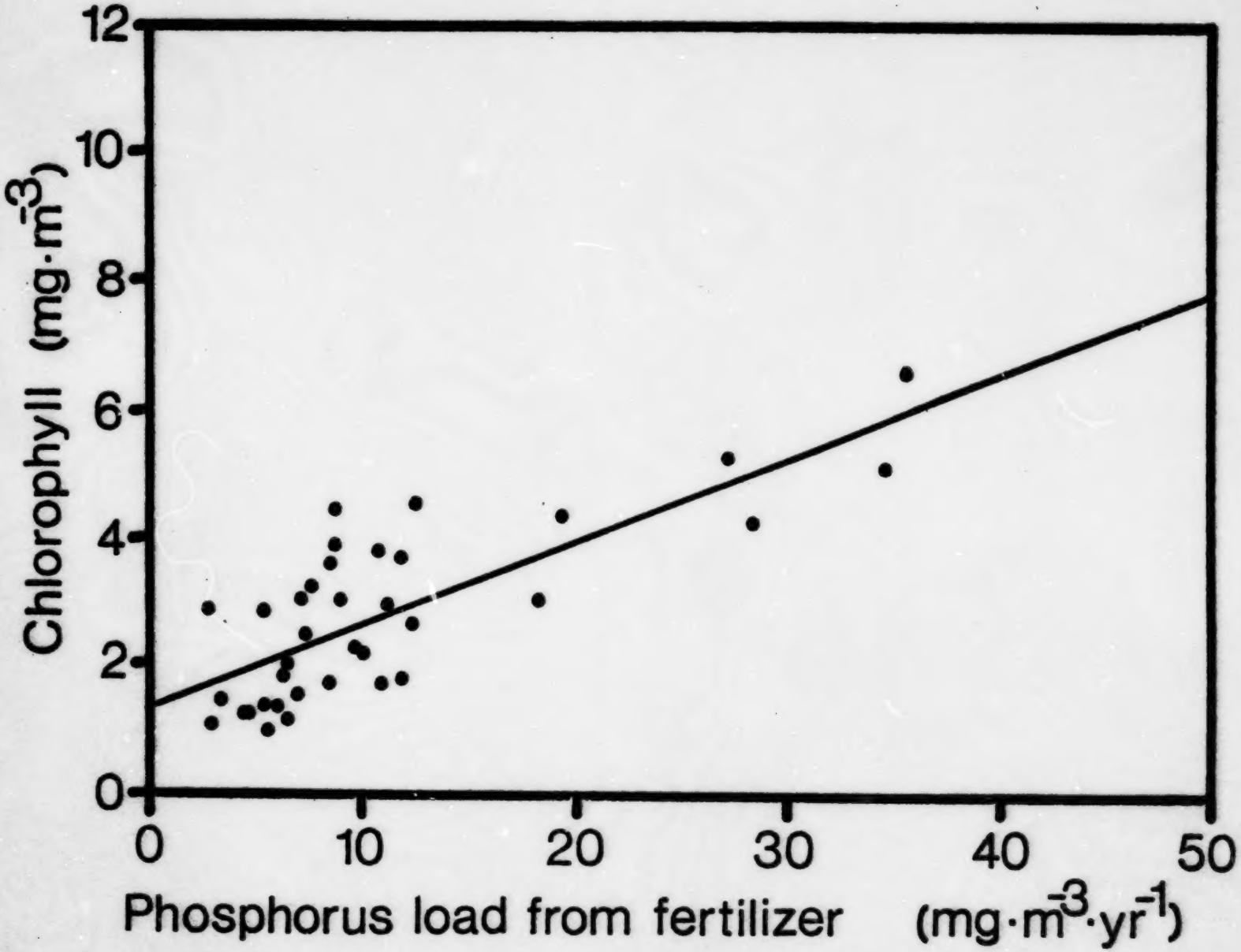


Figure 7. Relationship between average summer chlorophyll and phosphorus load from fertilizer applications. The phosphorus load is the total added to the lakes during the 20-26 week period each year when weekly fertilizer applications occurred. (r^2 = 0.62, $p<0.01$, n = 37; CHL = TP_f x 0.13 + 1.35).


Chlorophyll (mg·m-3)
12
10
8
6
4
2
0
0
10
20
30
40
50
Phosphorus load from fertilizer (mg·m-3·yr-1)

Chlorophyll (mg·m^{-3})
0
2
4
6
8
10
12
0
10
20
30
40
50
Phosphorus load from terrestrial (mg·m^{-2}·yr^{-1})

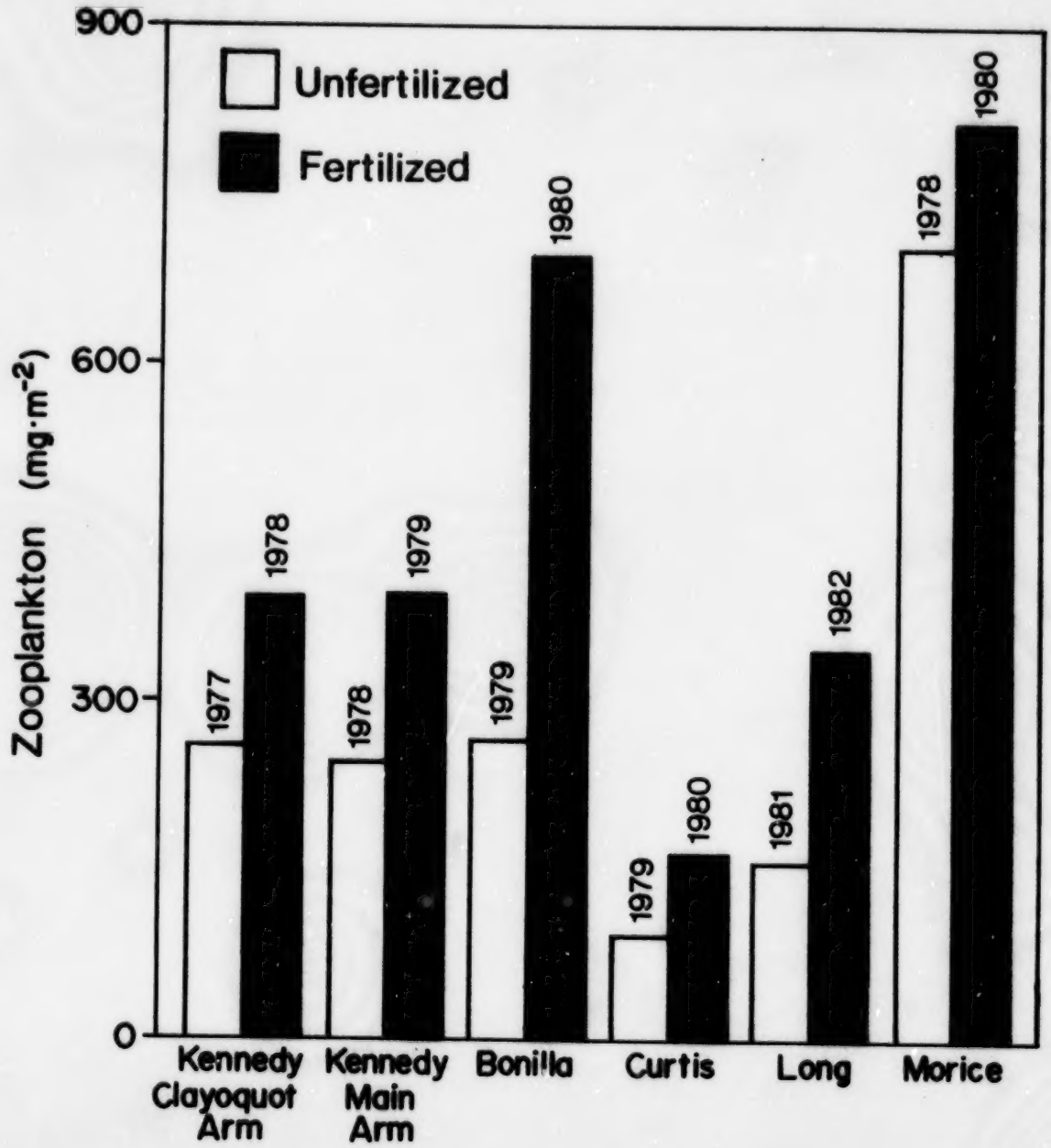


Figure 8. Seasonal average zooplankton biomass ($mg \cdot m^{-2}$) in several coastal lakes in the year preceeding and year of first fertilization.

APPENDIX

LAKE ENRICHMENT PROGRAM PUBLICATIONS

Lake Enrichment Program Publications 1977 - 1984

1977

Stockner, J. G. 1977. Lake fertilization as a means of enhancing sockeye salmon populations: the state of the art in the Pacific Northwest. Fish. Mar. Serv. Tech. Rep. 740: 14 p.

1978

LeBrasseur, R. J., C. D. McAllister, W. E. Barraclough, O. D. Kennedy, J. Manzer, D. Robinson, and K. Stephens. 1978. Enhancement of sockeye salmon (Oncorhynchus nerka) by lake fertilization in Great Central Lake: summary report. J. Fish. Res. Board Can. 35: 1580-1596.

Robinson, D. G., and W. E. Barraclough. 1978. Population estimates of sockeye salmon (Oncorhynchus nerka) in a fertilized oligotrophic lake. J. Fish. Res. Board Can. 35: 851-860.

Shortreed, K. S., and J. G. Stockner. 1978. Response of attached algae to whole-lake fertilization experiments in five British Columbia coastal lakes. Fish. Mar. Serv. Tech. Rep. 802: 25 p.

Stockner, J. G., and K. R. S. Shortreed. 1978. Limnological survey of 35 sockeye salmon (Oncorhynchus nerka) nursery lakes in British Columbia and the Yukon Territory. Fish. Mar. Serv. Tech. Rep. 827: 47 p.

1979

Costella, A. C., K. R. S. Shortreed, and J. G. Stockner. 1979. Phytoplankton fractionation studies in Great Central Lake, British Columbia: a nutrient enriched sockeye salmon (Oncorhynchus nerka) nursery lake. Fish. Mar. Serv. Tech. Rep. 880: 27 p.

Gjernes, T. 1979. A portable midwater trawling system for use in remote lakes. Fish. Mar. Serv. Tech. Rep. 888: 13 p.

LeBrassuer, R. J., C. D. McAllister, T. R. Parsons. 1979. Addition of nutrients to a lake leads to greatly increased catch of salmon. Environmental Conservation 6: 187-190.

Rankin, D. P., H. J. Ashton, and O. D. Kennedy. 1979. Crustacean zooplankton abundance and species composition in six experimentally fertilized British Columbia lakes. Fish. Mar. Serv. Tech. Rep. 897: 27 p.

Stockner, J. G. 1979. (Second Edition Revised). Lake fertilization as a means of enhancing sockeye salmon populations: the state of the art in the Pacific Northwest. Fish. Mar. Serv. Tech. Rep. 740: 14 p.

Stockner, J. G., and J. I. Manzer. 1979. Pilot scale lake fertilization studies in British Columbia sockeye salmon (Oncorhynchus nerka) nursery lakes: an overview. Preceedings of Biology of Pacific Salmons (USSR, USA, Canada and Japan) Oct. 3-13, 1978, Yuzhno-Sakhalinsk, USSR.

Stockner, J. G., and H. Seki. 1979. Pilot scale lake fertilization studies for enhancement of salmonid production. Science in Japan (in Japanese) 30(10): 19-22.

Stockner, J. G., and K. R. S. Shortreed. 1979. Limnological surveys of 13 sockeye salmon (Oncorhynchus nerka) nursery lakes in British Columbia. Fish. Mar. Serv. Tech. Rep. 880: 27 p.

1980

Rankin, D. P., and H. J. Ashton. 1980. Crustacean zooplankton abundance and species composition in 13 sockeye salmon (Oncorhynchus nerka) nursery lakes in British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 957: 39 p.

Seki, H., E. A. MacIsaac, and J. G. Stockner. 1980. The turnover rate of dissolved organic material in waters used by anadromous Pacific salmon on their return to Great Central Lake on Vancouver Island, British Columbia, Canada. Arch. Hydrobiol. 88: 58-72.

Seki, H., K. S. Shortreed, and J. G. Stockner. 1980. Turnover rate of dissolved organic materials in glacially oligotrophic lakes in British Columbia, Canada. Arch. Hydrobiol. 90(2): 210-215.

Stockner, J. G., K. R.S. Shortreed, and K. Stephens. 1980. The British Columbia lake fertilization program: limnological results from the first two years of treatment. Can. Tech. Rep. Fish. Aquat. Sci. 924: 91 p.

1981

MacIsaac, E. A., K. S. Shortreed, and J. G. Stockner. 1981. Seasonal distribution of bacterioplankton numbers and activities in eight fertilized or untreated oligotrophic British Columbia lakes. Can. Tech. Rep. Fish. Aquat. Sci. 994: 43 p.

Shortreed, K. S., and J. G. Stockner. 1981. Limnological results from the 1979 Lake Enrichment Program. Can. Tech. Rep. Fish. Aquat. Sci. 995: 71 p.

Simpson, K., L. Hop Wo, and I. Miki. 1981. Fish surveys of 15 sockeye salmon (Oncorhynchus nerka) nursery lakes in British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 1022: 87 p.

Stockner, J. G. 1981. Whole-lake fertilization for the enhancement of sockeye salmon (Oncorhynchus nerka) in British Columbia, Canada. Verh. Internat. Verein. Limnol. 21: 293-299.

1982

Costella, A. C., B. Nidle, R. Bocking, and K. S. Shortreed. 1982. Limnological results from the 1980 Lake Enrichment Program. Can. MS Rep. Fish. Aquat. Sci. 1635: 291 p.

Stockner, J. G., and C. D. Levings. (Editors). 1982. Biological reconnaissance of Yakoun River estuary, Queen Charlotte Islands, and results of a trial fertilization with urea. Can. Tech. Rep. Fish. Aquat. Sci. 1132: 119 p.

1983

Costella, A. C., B. Nidle and K. S. Shortreed. 1983. Limnological results from the 1981 British Columbia Lake Enrichment Program. Can. MS Rep. Fish. Aquat. Sci. 1693: 277 p.

Costella, A. C., B. Nidle and K. S. Shortreed. 1983. Limnological results from the 1982 British Columbia Lake Enrichment Program. Can. MS Rep. Fish. Aquat. Sci. 1706: 227 p.

Ishizaka, S., J. G. Stockner, K. Kobayashi, K. Shima, K. Katori, and H. Seki. 1983. Some elements comprising particulate matter in waters of various enviroments in British Columbia, Canada. Water Research (In press).

Stephens, K., and R. Brandstaetter. 1983. A laboratory manual: collected methods for the analysis of water. Can. Tech. Rep. Fish. Aquat. Sci. 1159: 68 p.

Stephens, K., and J. G. Stockner. 1983. The lake Enrichment Program: methods for the fertilization of lakes in British Columbia 1970-1982. Can. Tech. Rep. Fish. Aquat. Sci. 1192: 51 p.

Stockner, J. G., and K. S. Shortreed. 1983. A comparative limnological survey of 19 sockeye salmon (Oncorhynchus nerka) nursery lakes in the Fraser River system, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 1190: 63 p.

1984

Gjernes, T. 1984. Use of an uncalibrated echo sounder to estimate limnetic sockeye salmon populations. Can. Tech. Rep. Fish. Aquat. Sci. (In press).

Hyatt, K. G., and J. G. Stockner. 1985. Responses of sockeye salmon (Oncorhynchus nerka) to fertilization of British Columbia coastal lakes. Can. J. Fish. Aquat. Sci. (In press).

Manzer, J. I., M. Wright, I. Miki, and K. D. Hyatt. 1984. Abundance up-stream migration, age-composition and fecundity of Hobiton Lake adult sockeye salmon (Oncorhynchus nerka). Can. Tech. Rep. Fish. Aquat. Sci. (In press).

Nidle, B. H., K. S. Shortreed, and K. Masuda. 1984. Limnological results from the 1983 British Columbia Lake Enrichment Program. Can. MS Rep. Fish. Aquat. Sci. (In press).

Perrin, C., K. S. Shortreed, and J. G. Stockner. 1984. An integration of forest and lake fertilization: the transport and transportation of fertilizer elements. Can. J. Fish. Aquat. Sci. (In press).

Rankin, D. P., H. J. Ashton, and O. D. Kennedy. 1984. Zooplankton abundance in British Columbia lakes sampled by the Lake Enrichment Program in 1977. Can. Data Rep. Fish. Aquat. Sci. (In press).

Rankin, D. P., H. J. Ashton, and O. D. Kennedy. 1984. Zooplankton abundance in British Columbia lakes sampled by the Lake Enrichment Program in 1978. Part I. Vancouver Island. Can. Data Rep. Fish. Aquat. Sci. (In press).

Rankin, D. P., H. J. Ashton, and O. D. Kennedy. 1984. Zooplankton abundance in British Columbia lakes sampled by the Lake Enrichment Program in 1978. Part II. Central and North Coast. Can. Data Rep. Fish. Aquat. Sci. (In press).

Rankin, D. P. 1984. Zooplankton abundance and size in British Columbia lakes sampled by the Lake Enrichment Program in 1979 and 1980. Can. Data Rep. Fish. Aquat. Sci. (In press).

Shortreed, K. S., A. C. Costella, and J. G. Stockner. 1984. Periphyton biomass and species compositon in 21 British Columbia lakes: seasonal abundance and response to whole-lake nutrient additions. Can. J. Botany (In press).

Stockner, J. G., and K. S. Shortreed. 1985. Whole-lake fertilization experiments in coastal British Columbia lakes: empirical relationships between nutrient inputs and phytoplankton biomass and production. Can. J. Fish. Aquat. Sci. 41: (In press).